PATENT COOPERATION TREATY

OF

From the
INTERNATIONAL PRELIMINARY EXAMINING AUTHORITY

To:

PERKINS, Sarah
Stevens Hewlett & Perkins
Halton House
20/23 Holborn
London, Greater London EC1N 2JD
GRANDE BRETAGNE

PCT

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Rule 71.1)

	Date of mailing *(day/month/year)* 17.12.2001	
Applicant's or agent's file reference SP/4501 WO	**IMPORTANT NOTIFICATION**	
International application No. PCT/GB00/03496	International filing date *(day/month/year)* 12/09/2000	Priority date *(day/month/year)* 17/09/1999
Applicant ISIS INNOVATION LIMITED et al.		

1. The applicant is hereby notified that this International Preliminary Examining Authority transmits herewith the international preliminary examination report and its annexes, if any, established on the international application.

2. A copy of the report and its annexes, if any, is being transmitted to the International Bureau for communication to all the elected Offices.

3. Where required by any of the elected Offices, the International Bureau will prepare an English translation of the report (but not of any annexes) and will transmit such translation to those Offices.

4. **REMINDER**

The applicant must enter the national phase before each elected Office by performing certain acts (filing translations and paying national fees) within 30 months from the priority date (or later in some Offices) (Article 39(1)) (see also the reminder sent by the International Bureau with Form PCT/IB/301).

Where a translation of the international application must be furnished to an elected Office, that translation must contain a translation of any annexes to the international preliminary examination report. It is the applicant's responsibility to prepare and furnish such translation directly to each elected Office concerned.

For further details on the applicable time limits and requirements of the elected Offices, see Volume II of the PCT Applicant's Guide.

Name and mailing address of the IPEA/ European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	Authorized officer Marra, E Tel.+49 89 2399-7235

PATENT COOPERATION TREATY

PCT

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference SP/4501 WO	**FOR FURTHER ACTION**	See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416)
International application No. PCT/GB00/03496	International filing date *(day/month/year)* 12/09/2000	Priority date *(day/month/year)* 17/09/1999
International Patent Classification (IPC) or national classification and IPC B23K26/06		
Applicant ISIS INNOVATION LIMITED et al.		

1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.

2. This REPORT consists of a total of 7 sheets, including this cover sheet.

   ☒ This report is also accompanied by ANNEXES, i.e. sheets of the description, claims and/or drawings which have been amended and are the basis for this report and/or sheets containing rectifications made before this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions under the PCT).

   These annexes consist of a total of 4 sheets.

3. This report contains indications relating to the following items:

   I ☒ Basis of the report
   II ☐ Priority
   III ☐ Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   IV ☐ Lack of unity of invention
   V ☒ Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations suporting such statement
   VI ☐ Certain documents cited
   VII ☒ Certain defects in the international application
   VIII ☒ Certain observations on the international application

Date of submission of the demand 11/04/2001	Date of completion of this report 17.12.2001
Name and mailing address of the international preliminary examining authority: European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	Authorized officer Jeggy, T Telephone No. +49 89 2399 7341

I. Basis of the report

1. With regard to the **elements** of the international application *(Replacement sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to this report since they do not contain amendments (Rules 70.16 and 70.17))*:

Description, pages:

1,2,5-11	as originally filed			
3,4	as received on	28/09/2001	with letter of	25/09/2001

Claims, No.:

1-10	as received on	28/09/2001	with letter of	25/09/2001

Drawings, sheets:

1/4-4/4	as originally filed

2. With regard to the **language**, all the elements marked above were available or furnished to this Authority in the language in which the international application was filed, unless otherwise indicated under this item.

These elements were available or furnished to this Authority in the following language: , which is:

- ☐ the language of a translation furnished for the purposes of the international search (under Rule 23.1(b)).
- ☐ the language of publication of the international application (under Rule 48.3(b)).
- ☐ the language of a translation furnished for the purposes of international preliminary examination (under Rule 55.2 and/or 55.3).

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international preliminary examination was carried out on the basis of the sequence listing:

- ☐ contained in the international application in written form.
- ☐ filed together with the international application in computer readable form.
- ☐ furnished subsequently to this Authority in written form.
- ☐ furnished subsequently to this Authority in computer readable form.
- ☐ The statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.
- ☐ The statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished.

4. The amendments have resulted in the cancellation of:

☐ the description, pages:

☐ the claims, Nos.:

☐ the drawings, sheets:

5. ☐ This report has been established as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed (Rule 70.2(c)):

(Any replacement sheet containing such amendments must be referred to under item 1 and annexed to this report.)

6. Additional observations, if necessary:

V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	10
	No:	Claims	1-9
Inventive step (IS)	Yes:	Claims	
	No:	Claims	1-10
Industrial applicability (IA)	Yes:	Claims	1-10
	No:	Claims	

2. Citations and explanations
see separate sheet

VII. Certain defects in the international application

The following defects in the form or contents of the international application have been noted:
see separate sheet

VIII. Certain observations on the international application

The following observations on the clarity of the claims, description, and drawings or on the question whether the claims are fully supported by the description, are made:
see separate sheet

Re Item VIII

Certain observations on the international application

VIII.1 Claim 4 is not clear (Article 6 PCT). Claim 4 defines a laser conditioning apparatus for use in material processing of a workpiece, wherein the phase shifts of a plurality of regions being chosen in dependence on the desired intensity distribution of light incident on the workpiece which extends in at least one spatial dimension beyond the focused spot produced by laser apparatus in the absence of the filter. This statement is yet in contradiction with the wording of the new filed claims 1 and 9, wherein it is clearly stipulated that the intensity distribution extends in at least a spatial dimension parallel to the optical axis (see claims 1 and 9).

In this International preliminary Examination Report, claim 4 is examined with the following wording :

Cl 4 : laser conditioning apparatus for use in material processing of a workpiece, ... wherein the phase shifts of a plurality of regions being chosen in dependence on the desired intensity distribution of light incidence on the workpiece which extends ***in at least a spatial dimension parallel to the optical axis*** beyond the focused spot produced by laser apparatus in the absence of the filter.

Re Item V

Reasoned statement under Rule 66.2(a)(ii) with regard to novelty, inventive st p or industrial applicability; citations and explanations supporting such statement

V.1 Cited documents

Reference is made to the following documents :

D1 : EP-A_0 679 469 (MITSUBISHI DENKI KABUSHIKI KAISHA), 2 November 1995 (199-11-02)

D2 : US-A-5 481 407 (A.H. SMITH & al) 2 January 1996 (1996-01-02)

V.2 Claims 1-8

The document D1 discloses (the references in parentheses applying to this document) a laser conditioning apparatus (5) for use in material processing (page 1, lines 5-7) of a workpiece (8), the conditioning apparatus (5) comprising an adapter housing (part of 5, generating unit) containing a phase filter (other part of 5), the adapter housing (part of 5) having connection means for mounting the adapter housing (part of 5) between a coherent light source (1) and one or more focusing elements (7a, 7b, Figure 16), the phase filter (other part of 5) having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on the desired intensity distribution of light incident on the workpiece which extends in at least a spatial dimension parallel to the optical axis beyond the focused spot produced by laser apparatus in the absence of the filter (at least page 14, line 4 - page 15, line 57). Further D1 discloses also (the references in parentheses applying to this document) a laser apparatus (Figures 5-6 and 16) for use in material processing (page 1, lines 5-7) of a workpiece (8), the apparatus comprising a coherent or partially coherent light source (1), a housing (not shown) containing one or more focusing elements (7, 7a-7b on figure 16) and a phase filter (5), the phase filter (5) having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on a desired intensity distribution of light incident on the workpiece (8) which extends in at least a spatial dimension parallel to the optical axis beyond the focused spot produced by the apparatus in the absence of the filter (5 ; at least page 14, line 4 - page 15, line 57).

Indeed, as claims 1 and 4 define the phase filter, it also includes a normal dephasing filter (see Figure 6 of D1 for example). Furthermore, in a focused laser beam, the focalisation of the laser beam determines a spatial distribution of the intensity with the higher one at the focus point, i.e. increase of the intensity before the focus point ($z < 0$, with the same references as the one used in Figure 2 of the present application), maximum intensity at the focus point and then desired decrease of the intensity beyond the focus point. D1 describes also that the distribution of intensity is spatially modulated by the hologram (see also D1, page 14, lines 20-26 with the spatial modulation of the laser light), i.e. the intensity

distribution extends in at least a spatial dimension parallel to the optical axis beyond the focused point.

The subject-matter of claims 1 and 4 is therefore not new (Article 33 (2) PCT). Note that the subject-matter of claims 1 and 4 are also disclosed in D2 (Figures 2-35, 10 and 12 ; Column 8, line 58 - Column 9, line 23).

Dependent claims 2-3 and 5-8 do not contain any features which, in combination with the features of any claim to which they refer, meet the requirements of the PCT in respect of novelty (Article 33 (2) PCT) see D1 (Figures and cited passages in the international search report) for claims 2-3 and 5-8 ; see D2 (Figures 3a,5, 10 and 12) for claims 7-8.

V.3 Claims 9-10

The document D1 discloses (the references in parentheses applying to this document) a method of manufacturing a phase filter (5) for use in laser material processing apparatus (Figures 5-6 and 16 at least, the method comprising the steps of determining a desired intensity distribution of light incident on a workpiece which extends in at least a spatial dimension parallel to the optical axis beyond the focused spot produced by the laser material processing apparatus in the absence of the filter (5 ; page 16, lines 1-19); assigning initial respective phase shifts to a plurality of regions of the filter (5 ; page 16, lines 27-30) ; determining an error factor with respect to the similarity of the intensity distribution generated using the assigned phase shifts to the desired intensity distribution; iteratively optimising the phase shifts assigned to each region so as to determine final phase shifts for each region of the filter (page 16, lines 19-25) ; and generating a phase filter with a plurality of regions, each region having the final phase shift determined by the iterative optimisation step (page 16, lines 25-26) ; see also the argumentation given in Item V.2 concerning claims 1 and 4.

The subject-matter of claim 9 is therefore not new (Article 33 (2) PCT).

Concerning claim 10, it is considered to represent one of several straightforward possibilities from which the skilled person would select, in accordance with

circumstances, without the exercise of inventive skill (Article 33 (3) PCT), to optimised the phase shifts in a phase filter so that the machining of a workpiece is improved (see D1 using a computer program associated to the manufacturing of a general Fourier-transform phase filter (page 16 and page 17 until line 18 and also the other cited passages in this document which are cited in the search report).

Re Item VII

Certain defects in the international application

VII.1 Contrary to the requirements of Rule 5.1(a)(ii) PCT, the relevant background art disclosed in the document D1 is not mentioned in the description, nor is this document identified therein.

VII.2 Independent claims 1, 4 and 9 are not in the two-part form in accordance with Rule 6.3(b) PCT, which in the present case would be appropriate, with those features known in combination from the prior art (document D1) being placed in the preamble (Rule 6.3(b)(i) PCT) and with the remaining features being included in the characterising part (Rule 6.3(b)(ii) PCT).

VII.3 The features of the claims are not provided with reference signs placed in parentheses (Rule 6.2(b) PCT).

REPLACE BY ART 34 AMDT.

Replaced by Article 18 Mar 02

axis. The converter cannot alter the intensity distribution of the laser beam in any other way. In particular, the overall distribution of light intensity, the 'envelope' of the light intensity and/or the number of focal spots cannot be altered using the converter described in GB 2278458.

On the other hand, the present invention seeks to provide a novel optical arrangement that is capable of generating arbitrary predetermined three dimensional light intensity distributions that may be optimised for particular laser processing tasks.

The present invention provides laser apparatus for use in material processing of a workpiece, the apparatus comprising a coherent light source, a housing containing one or more focusing elements and a phase filter, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on a desired intensity distribution of light incident on the workpiece which extends in at least one spatial dimension beyond the focused spot produced by the apparatus in the absence of the filter..

In a preferred embodiment the phase filter is mounted between the one or more focussing elements and the workpiece. The phase filter may be provided in a removable cartridge that is removably mounted within the housing.

In an alternative aspect the present invention provides laser conditioning apparatus for use in material processing of a workpiece, the conditioning apparatus comprising an adapter housing containing a phase filter, the adapter housing having connection means for mounting the adapter housing between a coherent light source and one or more focusing elements, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on the desired intensity distribution of light incident on the workpiece which extends in at least one spatial dimension beyond the

focused spot produced by a laser apparatus in the absence of the filter.

Ideally, the plurality of phase shift regions of the filter produces an intensity distribution that extends beyond a diffraction limited focused spot in at least one spatial dimension. The phase filter may be arranged to produce a desired three dimensional geometry of the intensity distribution. Alternatively or in addition, the phase filter may produce a plurality of separate intensity peaks.

The phase shifts of the plurality of regions of the filter are iteratively optimised with respect to the desired intensity distribution of the light incident on the workpiece and preferably the phase shifts of the plurality of regions of the filter are iteratively optimised using a direct binary search.

In another aspect the present invention provides a method of manufacturing a phase filter for use in laser material processing apparatus, the method comprising the steps of: determining a desired intensity distribution of light incident on a workpiece which extends in at least one spatial dimension beyond the focused spot produced by the laser material processing apparatus in the absence of the filter; assigning initial respective phase shifts to a plurality of regions of the filter; determining an error factor with respect to the similarity of the intensity distribution generated using the assigned phase shifts to the desired intensity distribution; iteratively optimising the phase shifts assigned to each region so as to determine final phase shifts for each region of the filter; and generating a phase filter with a plurality of regions, each region having the final phase shift determined by the iterative optimisation step.

With the present invention there are very large degrees of freedom in the design of the phase-only filters and this makes it possible to achieve almost any desired intensity distribution defined in a three-dimensional volume around the lens focus. This, in turn, enables high precision, high speed and efficient material processing using a laser. Furthermore, the laser apparatus can be easily adjusted to produce an

CLAIMS

1. Laser apparatus for use in material processing of a workpiece, the apparatus comprising a coherent or partially coherent light source, a housing containing one or more focusing elements and a phase filter, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on a desired intensity distribution of light incident on the workpiece which extends in at least one spatial dimension beyond the focused spot produced by the apparatus in the absence of the filter.

2. Laser apparatus as claimed in claim 1, wherein the phase filter is mounted in the pupil plane of the one or more focussing elements.

3. Laser apparatus as claimed in either of claim 1, wherein the phase filter is provided in a removable cartridge that is removably mounted within the housing.

4. Laser conditioning apparatus for use in material processing of a workpiece, the conditioning apparatus comprising an adapter housing containing a phase filter, the adapter housing having connection means for mounting the adapter housing between a coherent light source and one or more focusing elements, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on the desired intensity distribution of light incident on the workpiece which extends in at least one spatial dimension beyond the focused spot produced by laser apparatus in the absence of the filter.

5. Apparatus as claimed in any one of the preceding claims, wherein the phase filter is a programmable spatial light modulator.

6. Apparatus as claimed in any one of the preceding claims, wherein each region of the filter has a phase shift of either 0 or π radians.

7. Apparatus as claimed in any one of the preceding claims, wherein the phase filter produces a desired three dimensional geometry of the light incident on the workpiece.

8. Apparatus as claimed in any one of the preceding claims, wherein the phase filter produces a plurality of separate intensity peaks.

9. Apparatus as claimed in any one of the preceding claims, wherein the phase shifts of the plurality of regions of the filter are iteratively optimised with respect to the desired intensity distribution of the light incident on the workpiece.

10. Apparatus as claimed in claim 9, wherein the phase shifts of the plurality of regions of the filter are iteratively optimised using a direct binary search.

11. A method of manufacturing a phase filter for use in laser material processing apparatus, the method comprising the steps of: determining a desired intensity distribution of light incident on a workpiece which extends in at least one spatial dimension beyond the focused spot produced by the laser material processing apparatus in the absence of the filter; assigning initial respective phase shifts to a plurality of regions of the filter; determining an error factor with respect to the similarity of the intensity distribution generated using the assigned phase shifts to the desired intensity distribution; iteratively optimising the phase shifts

assigned to each region so as to determine final phase shifts for each region of the filter; and generating a phase filter with a plurality of regions, each region having the final phase shift determined by the iterative optimisation step.

12. A method as claimed in claim 11, wherein the assigned phase shifts are iteratively optimised using a direct binary search.

PATENT COOPERATION TREATY

From the INTERNATIONAL BUREAU

PCT

NOTIFICATION OF ELECTION

(PCT Rule 61.2)

To:

Commissioner
US Department of Commerce
United States Patent and Trademark
Office, PCT
2011 South Clark Place Room
CP2/5C24
Arlington, VA 22202
ETATS-UNIS D'AMERIQUE

in its capacity as elected Office

Date of mailing (day/month/year) 14 May 2001 (14.05.01)	
International application No. PCT/GB00/03496	**Applicant's or agent's file reference** SP/4501 WO
International filing date (day/month/year) 12 September 2000 (12.09.00)	**Priority date** (day/month/year) 17 September 1999 (17.09.99)
Applicant LACZIK, Zsolt, John et al	

1. The designated Office is hereby notified of its election made:

   [X] in the demand filed with the International Preliminary Examining Authority on:

   11 April 2001 (11.04.01)

   [ ] in a notice effecting later election filed with the International Bureau on:

2. The election [X] was [ ] was not

   made before the expiration of 19 months from the priority date or, where Rule 32 applies, within the time limit under Rule 32.2(b).

The International Bureau of WIPO **34, chemin des Colombettes** **1211 Geneva 20, Switzerland** Facsimile No.: (41-22) 740.14.35	Authorized officer Zakaria EL KHODARY Telephone No.: (41-22) 338.83.38

ATENT COOPERATION TREA

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference SP/4501 WO	**FOR FURTHER ACTION** see Notification of Transmittal of International Search Report (Form PCT/ISA/220) as well as, where applicable, item 5 below.	
International application No. PCT/GB 00/ 03496	International filing date *(day/month/year)* 12/09/2000	(Earliest) Priority Date *(day/month/year)* 17/09/1999
Applicant ISIS INNOVATION LIMITED		

This International Search Report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This International Search Report consists of a total of 03 sheets.

[X] It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**

   a. With regard to the **language**, the international search was carried out on the basis of the international application in the language in which it was filed, unless otherwise indicated under this item.

      [ ] the international search was carried out on the basis of a translation of the international application furnished to this Authority (Rule 23.1(b)).

   b. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international search was carried out on the basis of the sequence listing :

      [ ] contained in the international application in written form.
      [ ] filed together with the international application in computer readable form.
      [ ] furnished subsequently to this Authority in written form.
      [ ] furnished subsequently to this Authority in computer readble form.
      [ ] the statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.
      [ ] the statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished

2. [ ] **Certain claims were found unsearchable** (See Box I).

3. [ ] **Unity of invention is lacking** (see Box II).

4. With regard to the **title**,

   [X] the text is approved as submitted by the applicant.
   [ ] the text has been established by this Authority to read as follows:

5. With regard to the **abstract**,

   [X] the text is approved as submitted by the applicant.
   [ ] the text has been established, according to Rule 38.2(b), by this Authority as it appears in Box III. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.

6. The figure of the **drawings** to be published with the abstract is Figure No. 1A

   [ ] as suggested by the applicant.
   [ ] because the applicant failed to suggest a figure.
   [ ] because this figure better characterizes the invention.

   [ ] None of the figures.

3

PATENT COOPERATION TREATY

REC'D 19 DEC 2001

WIPO PCT

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INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference SP/4501 WO	**FOR FURTHER ACTION** See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416)	
International application No. PCT/GB00/03496	International filing date *(day/month/year)* 12/09/2000	Priority date *(day/month/year)* 17/09/1999
International Patent Classification (IPC) or national classification and IPC B23K26/06		
Applicant ISIS INNOVATION LIMITED et al.		

1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.

2. This REPORT consists of a total of 7 sheets, including this cover sheet.

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3. This report contains indications relating to the following items:

   I ☒ Basis of the report
   II ☐ Priority
   III ☐ Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   IV ☐ Lack of unity of invention
   V ☒ Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations suporting such statement
   VI ☐ Certain documents cited
   VII ☒ Certain defects in the international application
   VIII ☒ Certain observations on the international application

Date of submission of the demand 11/04/2001	Date of completion of this report 17.12.2001
Name and mailing address of the international preliminary examining authority: European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	Authorized officer Jeggy, T Telephone No. +49 89 2399 7341

I. Basis of the report

1. With regard to the **elements** of the international application *(Replacement sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to this report since they do not contain amendments (Rules 70.16 and 70.17))*:

Description, pages:

1,2,5-11	as originally filed			
3,4	as received on	28/09/2001	with letter of	25/09/2001

Claims, No.:

1-10	as received on	28/09/2001	with letter of	25/09/2001

Drawings, sheets:

1/4-4/4	as originally filed

2. With regard to the **language**, all the elements marked above were available or furnished to this Authority in the language in which the international application was filed, unless otherwise indicated under this item.

These elements were available or furnished to this Authority in the following language: , which is:

- ☐ the language of a translation furnished for the purposes of the international search (under Rule 23.1(b)).
- ☐ the language of publication of the international application (under Rule 48.3(b)).
- ☐ the language of a translation furnished for the purposes of international preliminary examination (under Rule 55.2 and/or 55.3).

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international preliminary examination was carried out on the basis of the sequence listing:

- ☐ contained in the international application in written form.
- ☐ filed together with the international application in computer readable form.
- ☐ furnished subsequently to this Authority in written form.
- ☐ furnished subsequently to this Authority in computer readable form.
- ☐ The statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.
- ☐ The statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished.

4. The amendments have resulted in the cancellation of:

☐ the description, pages:

☐ the claims, Nos.:

☐ the drawings, sheets:

5. ☐ This report has been established as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed (Rule 70.2(c)):

   (Any replacement sheet containing such amendments must be referred to under item 1 and annexed to this report.)

6. Additional observations, if necessary:

V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	10
	No:	Claims	1-9
Inventive step (IS)	Yes:	Claims	
	No:	Claims	1-10
Industrial applicability (IA)	Yes:	Claims	1-10
	No:	Claims	

2. Citations and explanations
   see separate sheet

VII. Certain defects in the international application

The following defects in the form or contents of the international application have been noted:
see separate sheet

VIII. Certain observations on the international application

The following observations on the clarity of the claims, description, and drawings or on the question whether the claims are fully supported by the description, are made:
see separate sheet

Re Item VIII
Certain observations on the international application

VIII.1 Claim 4 is not clear (Article 6 PCT). Claim 4 defines a laser conditioning apparatus for use in material processing of a workpiece, wherein the phase shifts of a plurality of regions being chosen in dependence on the desired intensity distribution of light incident on the workpiece which extends in at l ast one spatial dimension beyond the focused spot produced by laser apparatus in the absence of the filter. This statement is yet in contradiction with the wording of the new filed claims 1 and 9, wherein it is clearly stipulated that the intensity distribution extends in at least a spatial dimension parallel to the optical axis (see claims 1 and 9).

In this International preliminary Examination Report, claim 4 is examined with the following wording :

Cl 4 : laser conditioning apparatus for use in material processing of a workpiece, ... wherein the phase shifts of a plurality of regions being chosen in dependence on the desired intensity distribution of light incidence on the workpiece which extends ***in at least a spatial dimension parallel to the optical axis*** beyond the focused spot produced by laser apparatus in the absence of the filter.

Re Item V
Reasoned statement under Rule 66.2(a)(ii) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

V.1 Cited documents

Reference is made to the following documents :

D1 : EP-A_0 679 469 (MITSUBISHI DENKI KABUSHIKI KAISHA), 2 November 1995 (199-11-02)

D2 : US-A-5 481 407 (A.H. SMITH & al) 2 January 1996 (1996-01-02)

V.2 Claims 1-8

The document D1 discloses (the references in parentheses applying to this document) a laser conditioning apparatus (5) for use in material processing (page 1, lines 5-7) of a workpiece (8), the conditioning apparatus (5) comprising an adapter housing (part of 5, generating unit) containing a phase filter (other part of 5), the adapter housing (part of 5) having connection means for mounting the adapter housing (part of 5) between a coherent light source (1) and one or more focusing elements (7a, 7b, Figure 16), the phase filter (other part of 5) having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on the desired intensity distribution of light incident on the workpiece which extends in at least a spatial dimension parallel to the optical axis beyond the focused spot produced by laser apparatus in the absence of the filter (at least page 14, line 4 - page 15, line 57). Further D1 discloses also (the references in parentheses applying to this document) a laser apparatus (Figures 5-6 and 16) for use in material processing (page 1, lines 5-7) of a workpiece (8), the apparatus comprising a coherent or partially coherent light source (1), a housing (not shown) containing one or more focusing elements (7, 7a-7b on figure 16) and a phase filter (5), the phase filter (5) having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions b ing chosen in dependence on a desired intensity distribution of light incident on the workpiece (8) which extends in at least a spatial dimension parallel to the optical axis beyond the focused spot produced by the apparatus in the absence of the filter (5 ; at least page 14, line 4 - page 15, line 57).

Indeed, as claims 1 and 4 define the phase filter, it also includes a normal dephasing filter (see Figure 6 of D1 for example). Furthermore, in a focused laser beam, the focalisation of the laser beam determines a spatial distribution of the intensity with the higher one at the focus point, i.e. increase of the intensity before the focus point ($z < 0$, with the same references as the one used in Figure 2 of the present application), maximum intensity at the focus point and then desired decrease of the intensity beyond the focus point. D1 describes also that the distribution of intensity is spatially modulated by the hologram (see also D1, page 14, lines 20-26 with the spatial modulation of the laser light), i.e. the intensity

distribution extends in at least a spatial dimension parallel to the optical axis beyond the focused point.

The subject-matter of claims 1 and 4 is therefore not new (Article 33 (2) PCT). Note that the subject-matter of claims 1 and 4 are also disclosed in D2 (Figures 2-35, 10 and 12 ; Column 8, line 58 - Column 9, line 23).

Dependent claims 2-3 and 5-8 do not contain any features which, in combination with the features of any claim to which they refer, meet the requirements of the PCT in respect of novelty (Article 33 (2) PCT) see D1 (Figures and cited passages in the international search report) for claims 2-3 and 5-8 ; see D2 (Figures 3a,5, 10 and 12) for claims 7-8.

V.3 Claims 9-10

The document D1 discloses (the references in parentheses applying to this document) a method of manufacturing a phase filter (5) for use in laser material processing apparatus (Figures 5-6 and 16 at least, the method comprising the steps of determining a desired intensity distribution of light incident on a workpiece which extends in at least a spatial dimension parallel to the optical axis beyond the focused spot produced by the laser material processing apparatus in the absence of the filter (5 ; page 16, lines 1-19); assigning initial respective phase shifts to a plurality of regions of the filter (5 ; page 16, lines 27-30) ; determining an error factor with respect to the similarity of the intensity distribution generated using the assigned phase shifts to the desired intensity distribution; iteratively optimising the phase shifts assigned to each region so as to determine final phase shifts for each region of the filter (page 16, lines 19-25) ; and generating a phase filter with a plurality of regions, each region having the final phase shift determined by the iterative optimisation step (page 16, lines 25-26) ; see also the argumentation given in Item V.2 concerning claims 1 and 4.

The subject-matter of claim 9 is therefore not new (Article 33 (2) PCT).

Concerning claim 10, it is considered to represent one of several straightforward possibilities from which the skilled person would select, in accordance with

circumstances, without the exercise of inventive skill (Article 33 (3) PCT), to optimised the phase shifts in a phase filter so that the machining of a workpiece is improved (see D1 using a computer program associated to the manufacturing of a general Fourier-transform phase filter (page 16 and page 17 until line 18 and also the other cited passages in this document which are cited in the search report).

Re Item VII

Certain defects in the international application

VII.1 Contrary to the requirements of Rule 5.1(a)(ii) PCT, the relevant background art disclosed in the document D1 is not mentioned in the description, nor is this document identified therein.

VII.2 Independent claims 1, 4 and 9 are not in the two-part form in accordance with Rule 6.3(b) PCT, which in the present case would be appropriate, with those features known in combination from the prior art (document D1) being placed in the preamble (Rule 6.3(b)(i) PCT) and with the remaining features being included in the characterising part (Rule 6.3(b)(ii) PCT).

VII.3 The features of the claims are not provided with reference signs placed in parentheses (Rule 6.2(b) PCT).

axis. The converter cannot alter the intensity distribution of the laser beam in any other way. In particular, the overall distribution of light intensity, the 'envelope' of the light intensity and/or the number of focal spots cannot be altered using the converter described in GB 2278458.

On the other hand, the present invention seeks to provide a novel optical arrangement that is capable of generating arbitrary predetermined three dimensional light intensity distributions that may be optimised for particular laser processing tasks.

The present invention provides laser apparatus for use in material processing of a workpiece, the apparatus comprising a coherent light source, a housing containing one or more focusing elements and a phase filter, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on a desired intensity distribution of light incident on the workpiece which extends in at least a spatial dimension parallel to the optical axis beyond the focused spot produced by the apparatus in the absence of the filter..

In a preferred embodiment the phase filter is mounted between the one or more focussing elements and the workpiece. The phase filter may be provided in a removable cartridge that is removably mounted within the housing.

In an alternative aspect the present invention provides laser conditioning apparatus for use in material processing of a workpiece, the conditioning apparatus comprising an adapter housing containing a phase filter, the adapter housing having connection means for mounting the adapter housing between a coherent light source and one or more focusing elements, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on the desired intensity distribution of light incident on the workpiece which extends in at least a spatial dimension parallel to the

optical axis beyond the focused spot produced by a laser apparatus in the absence of the filter.

Ideally, the plurality of phase shift regions of the filter produces an intensity distribution that extends beyond a diffraction limited focused spot in at least one spatial dimension. The phase filter may be arranged to produce a desired three dimensional geometry of the intensity distribution. Alternatively or in addition, the phase filter may produce a plurality of separate intensity peaks.

The phase shifts of the plurality of regions of the filter are iteratively optimised with respect to the desired intensity distribution of the light incident on the workpiece and preferably the phase shifts of the plurality of regions of the filter are iteratively optimised using a direct binary search.

In another aspect the present invention provides a method of manufacturing a phase filter for use in laser material processing apparatus, the method comprising the steps of: determining a desired intensity distribution of light incident on a workpiece which extends in at least one spatial dimension beyond the focused spot produced by the laser material processing apparatus in the absence of the filter; assigning initial respective phase shifts to a plurality of regions of the filter; determining an error factor with respect to the similarity of the intensity distribution generated using the assigned phase shifts to the desired intensity distribution; iteratively optimising the phase shifts assigned to each region so as to determine final phase shifts for each region of the filter; and generating a phase filter with a plurality of regions, each region having the final phase shift determined by the iterative optimisation step.

With the present invention there are very large degrees of freedom in the design of the phase-only filters and this makes it possible to achieve almost any desired intensity distribution defined in a three-dimensional volume around the lens focus. This, in turn, enables high precision, high speed and efficient material processing using a laser. Furthermore, the laser apparatus can be easily adjusted to produce an

CLAIMS

1. Laser apparatus for use in material processing of a workpiece, the apparatus comprising a coherent or partially coherent light source, a housing containing one or more focusing elements and a phase filter, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on a desired intensity distribution of light incident on the workpiece which extends in at least a spatial dimension parallel to the optical axis beyond the focused spot produced by the apparatus in the absence of the filter.

2. Laser apparatus as claimed in claim 1, wherein the phase filter is mounted in the pupil plane of the one or more focussing elements.

3. Laser apparatus as claimed in either of claim 1, wherein the phase filter is provided in a removable cartridge that is removably mounted within the housing.

4. Laser conditioning apparatus for use in material processing of a workpiece, the conditioning apparatus comprising an adapter housing containing a phase filter, the adapter housing having connection means for mounting the adapter housing between a coherent light source and one or more focusing elements, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on the desired intensity distribution of light incident on the workpiece which extends in at least one spatial dimension beyond the focused spot produced by laser apparatus in the absence of the filter.

5. Apparatus as claimed in any one of the preceding claims, wherein the phase filter is a programmable spatial light modulator.

6. Apparatus as claimed in any one of the preceding claims, wherein each region of the filter has a phase shift of either 0 or π radians.

7. Apparatus as claimed in any one of the preceding claims, wherein the phase filter produces a desired three dimensional geometry of the light incident on the workpiece.

8. Apparatus as claimed in any one of the preceding claims, wherein the phase filter produces a plurality of separate intensity peaks.

9. A method of manufacturing a phase filter for use in laser material processing apparatus, the method comprising the steps of: determining a desired intensity distribution of light incident on a workpiece which extends in at least a spatial dimension parallel to the optical axis beyond the focused spot produced by the laser material processing apparatus in the absence of the filter; assigning initial respective phase shifts to a plurality of regions of the filter; determining an error factor with respect to the similarity of the intensity distribution generated using the assigned phase shifts to the desired intensity distribution; iteratively optimising the phase shifts assigned to each region so as to determine final phase shifts for each region of the filter; and generating a phase filter with a plurality of regions, each region having the final phase shift determined by the iterative optimisation step.

10. A method as claimed in claim 9, wherein the assigned phase shifts are iteratively optimised using a direct binary search.

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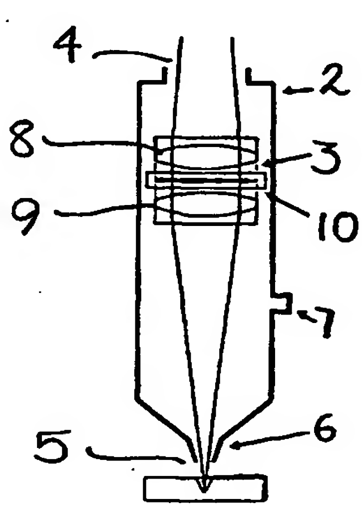
(54) Title: LASER APPARATUS FOR USE IN MATERIAL PROCESSING



(57) Abstract: The laser has a focusing system including a housing (2) with opposing transparent windows (4, 5) between which imaging optics (3) are positioned. The housing (2) also has an inlet (7) for the introduction of pressurised gas into the cavity of the housing. The imaging optics (3) include refractive/reflective lens elements (8, 9) and a phase-only filter (10). The filter (10) has different regions each assigned a particular phase-shift and may be implemented in the pixels of a spatial light modulator or using a fused silica structure that has regions etched to differing depths to achieve differing phase delays by means of the remaining thickness of the silica at each of the regions. The filter (10) ensures that the laser beam incident on a workpiece that is to be cut, for example, has an intensity distribution which extends beyond the focussed spot in at least one dimension. With this laser high precision as well as high speed cutting or welding can be performed using an optimised light distribution.

WO 01/21353 A1

LASER APPARATUS FOR USE IN MATERIAL PROCESSING

The present invention relates to laser apparatus for use in material processing and in particular but not exclusively for use in cutting, welding, machining and other related processing techniques of materials.

In conventional laser cutting, welding and machining systems light from a CW or pulsed laser is focused to an approximately diffraction limited spot using refractive lens elements and/or reflective mirrors. When the focused spot is brought into contact with a workpiece the very high light intensity in the focused spot results in localised heating of the workpiece and consequently localised melting, evaporation or ablation of the material occurs. Normally a gas flow co-axial with the optical system is also provided to protect the lens elements by forcing sputtered material away from the lens elements and to enhance the cutting, welding or machining process. In the case of welding the gas is usually inert but for cutting the gas may be corrosive and contribute to the cutting process. The focused spot and the workpiece must be moved with respect to one another in such a way that the workpiece is welded, cut or machined in pre-defined areas.

In many cases, however, the optimum light intensity distribution for the process described above is not the one corresponding to a single diffraction limited focused spot. Instead, it has been found that in some cases the use of two focused spots separated by a few millimetres can be advantageous.

In WO 98/14302 laser cutting apparatus is described in which the light from the laser is imaged to two separated focal points on a common axis by means of a multi-lens or a curved reflective surface. Similarly, in US5521352 laser apparatus for cutting a metal workpiece is described which uses a semi-silvered mirror to split the light from the laser into two beams. The two beams are then directed, using conventional reflective optics, to opposing surfaces of the workpiece.

With the apparatus described in the documents referr d to

above the light from a laser beam is focussed to two separated focal spots using conventional refractive/reflective optical elements. In general, the apparatus have very limited degrees of freedom and are inflexible. For example, in WO 98/14302 the only selectable design parameters are the radius of the central region of the lens element and the difference in curvature between the central region and the annulus. This significantly restricts the extent to which characteristics such as the separation between the foci, the power split ratio and the axial and spatial resolution of the foci may be selected and in some cases the opportunity for selection of such characteristics is not available.

Also, once the design parameters are chosen and a lens element with the appropriate radii of the central region and the annulus is provided, the apparatus is only capable of generating the two focal spots as determined by that lens element. To alter the performance characteristics of the apparatus, a completely new alternative lens element would have to replace the existing lens element. Furthermore, it should be noted that the laser cutting apparatus described in the documents referred to above are limited to specific intensity distributions associated with the two separate focus spots.

In GB2278458 a converter for a laser is described that adjusts the intensity profile of the laser beam across a single focused spot. The converter consists of a phase zone plate array consisting of a two dimensional array of close packed diffracting Fresnel zone plates randomly arranged to cause a phase delay of 0 or π radians. The converter is used to reduce fluctuations in intensity across the focal spot and thereby ensures a more uniform focal spot is produced. However, with the converter only the intensity across the focal spot itself is adjusted, the intensity distribution is not altered such that the adjusted distribution extends beyond the focused spot that would be produced without the converter in place. Furthermore, the adjustment of the intensity distribution to increase th uniformity of the intensity is restricted to a plane perpendicular to the optical

axis. The converter cannot alter the intensity distribution of th laser beam in any other way. In particular, the overall distribution of light intensity, the 'envelope' of the light intensity and/or the number of focal spots cannot be altered using the converter described in GB 2278458.

On the other hand, the present invention seeks to provide a novel optical arrangement that is capable of generating arbitrary predetermined three dimensional light intensity distributions that may be optimised for particular laser processing tasks.

The present invention provides laser apparatus for use in material processing of a workpiece, the apparatus comprising a coherent light source, a housing containing one or more focusing elements and a phase filter, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on a desired intensity distribution of light incident on the workpiece which extends in at least one spatial dimension beyond the focused spot produced by the apparatus in the absence of the filter..

In a preferred embodiment the phase filter is mounted between the one or more focussing elements and the workpiece. The phase filter may be provided in a removable cartridge that is removably mounted within the housing.

In an alternative aspect the present invention provides laser conditioning apparatus for use in material processing of a workpiece, the conditioning apparatus comprising an adapter housing containing a phase filter, the adapter housing having connection means for mounting the adapter housing between a coherent light source and one or more focusing elements, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on the desired intensity distribution of light incident on the workpiece which extends in at least one spatial dimension beyond the

focused spot produced by a laser apparatus in the absence of the filter.

Ideally, the plurality of phase shift regions of the filter produces an intensity distribution that extends beyond a diffraction limited focused spot in at least one spatial dimension. The phase filter may be arranged to produce a desired three dimensional geometry of the intensity distribution. Alternatively or in addition, the phase filter may produce a plurality of separate intensity peaks.

The phase shifts of the plurality of regions of the filter are iteratively optimised with respect to the desired intensity distribution of the light incident on the workpiece and preferably the phase shifts of the plurality of regions of the filter are iteratively optimised using a direct binary search.

In another aspect the present invention provides a method of manufacturing a phase filter for use in laser material processing apparatus, the method comprising the steps of: determining a desired intensity distribution of light incident on a workpiece which extends in at least one spatial dimension beyond the focused spot produced by the laser material processing apparatus in the absence of the filter; assigning initial respective phase shifts to a plurality of regions of the filter; determining an error factor with respect to the similarity of the intensity distribution generated using the assigned phase shifts to the desired intensity distribution; iteratively optimising the phase shifts assigned to each region so as to determine final phase shifts for each region of the filter; and generating a phase filter with a plurality of regions, each region having the final phase shift determined by the iterative optimisation step.

With the present invention there are very large degrees of freedom in the design of the phase-only filters and this makes it possible to achieve almost any desired intensity distribution defined in a three-dimensional volume around the lens focus. This, in turn, enables high precision, high speed and efficient material processing using a laser. Furthermore, the laser apparatus can be easily adjusted to produce an

alternative intensity distribution simply by altering or replacing the phase-only filter, the main and more expensive part of the apparatus, the focusing lens, can be retained and reused. Where a spatial light modulator is used as the phase-only filter, alteration of the intensity distribution is simply a matter of re-programming the modulator and so the laser apparatus is very flexible and responsive to the individual intensity distribution requirements of particular processing tasks.

It will, of course, be understood that although reference is made herein to laser sources this is intended to generally cover both coherent and partially coherent laser sources.

An embodiment of the present invention will now be described by way of example with reference to the accompanying drawings, in which:

Figures 1a, 1b and 1c are schematic diagrams of a laser focusing system in accordance with the present invention with the phase-only filter in different positions;

Figure 2 is a schematic diagram of a conventional laser focusing system with an adapter incorporating a phase-only filter in accordance with the present invention;

Figures 3, 4 and 5 are tables of phase-only filter designs and the intensity distributions in the XZ and YZ planes produced using the filters.

As shown in Figures 1a, 1b and 1c a laser focusing system suitable for use in processing of a workpiece consists of a housing 2 that is generally cylindrical within which is positioned imaging optics 3. The housing 2 has opposing windows 4, 5 at each end of the housing, aligned with the imaging optics 3, through which the laser beam passes. The housing 2 also includes a nozzle 6 that is positioned over the work piece when in use and a fluid inlet 7 for the introduction of a pressurised gas into the cavity of the housing. Although not shown, a light source in the form of a laser is aligned with the windows 4, 5 so as to illuminate the workpiece

through the focusing system. The laser may be any one of the many commercially available lasers such as CO_2, excimer or YAG lasers. These lasers are capable of generating light over a broad range of wavelengths from, for example 193 nm with an excimer laser to 10.6 μm with a CO_2 laser.

The imaging optics 3 consists of refractive/reflective lens elements 8,9 (refractive lenses are shown in Figure 1) for producing a single diffraction limited focus and a phase-only filter 10. The phase-only filter 10 may be positioned in the pupil plane of the focusing lens elements as shown in Figure 1a. Alternatively, the filter 10 may be positioned between the lens elements 8, 9 and the workpiece as shown in Figure 1b or between the lens elements 8, 9 and the laser as shown in Figure 1c. The phase-only filter 10 may be fixed in the imaging optics 3 or may be provided in a cartridge that is removably inserted into imaging optics so as to simplify replacement of the filter 10 with alternative phase-only filters, in dependence on the filter most suitable for the particular processing task to be performed.

As shown in Figure 2, laser conditioning apparatus in the form of an adapter 11 may be provided in the form of a cylindrical tube within which is mounted the phase-only filter 10. The adapter 11 includes engaging means for connecting the adapter to the housing of a conventional laser focusing system, between the laser and the window to the housing. In this way, a conventional laser focusing system can be retro-fitted with the phase-only filter so as to enable greater flexibility in the intensity distributions generated by the laser focusing system for use in material processing.

The phase-only filter is preferably square or circular and has a diameter that ideally corresponds to the diameter of the lens elements, for example 38 mm. The filter consists of a plurality of individual regions each assigned a respective phase shift, with the phase shift of each region determined using optimisation software to achieve a predetermined or

target intensity distribution defined in a 3D volume around the original lens focus. Where the filter is a binary filter the individual pixels of the filter cause either a 0 or π radians phase delay. However, more complex filters are also envisaged additionally incorporating phase shifts of $1/2\pi$ radians and $3/2\pi$ radians, for example. The filter may be a pixellated filter in the form of a programmable spatial light modulator, for example. One preferred filter employs an array of 128 x 128, however, arrays of 1,000 x 1,000 or more are also envisaged. Alternative filters may incorporate ring-shaped, hexagonal or even irregular regions each assigned a predetermined phase shift.

The filter 10 may be fabricated from a fused silica substrate using conventional techniques. For example, a layer of photoresist is applied to the surface of a fused silica substrate. The predetermined design of the filter is then patterned in the photoresist using a chrome mask and conventional contact printing or projection lithographic techniques. The photoresist exposed through the chrome mask is subsequently etched to expose regions of the silica substrate and the exposed silica is then patterned by etching the exposed regions of the silica through the remaining photoresist. The exposed silica is etched to a predetermined depth to achieve the desire phase delay Φ and the remaining photoresist is subsequently removed. The etched depth may be calculated using the following equation:

$$h = \frac{\Phi}{2\pi} \cdot \frac{\lambda}{n - n_0}$$

where h is the etch depth, λ is the wavelength of the incident light, n is the refractive index of the substrate and n_0 is the refractive index of the environment. Thus, for a phase delay of π radians the etch depth is $\lambda/2(n-n_0)$.

The optimisation software, used to determine the design of the filter for any particular target intensity distribution, may employ iterative algorithms such as Direct Binary Search or an iterative inverse Fourier

transform to determine the particular design of the filter. For example, to design a filter for a target intensity distribution $I_T(x,y,z)$ at and around the original lens-only focus, a set of N_T discrete points (x_m,y_m,z_m) are selected in such a way that the intensities at the points $I_{Tm}(x_m,y_m,z_m)$ can serve as a representative set for the continuous distribution $I_T(x,y,z)$.

The lens pupil and the filter are then divided into N_P regions (pixels). By using Fourier optics theory, or by directly evaluating the optical diffraction integrals, the complex amplitudes due to the individual lens regions, the lens pixels, are then calculated at the target points. These lens-only 'pixel contributions' are denoted A_{Lmn}, where $m=1..N_T$ and $n=1..N_P$.

Also, the effect of the phase-only filter is assumed to be a constant Φ_n phase shift within each pixel. The complex amplitude pixel contributions due to the combination of the lens and the filter can then be written as $A_{mn}=A_{Lmn}\exp(i\Phi_n)$.

For any given set of Φ_n pixel phase shift values, the complex amplitudes and intensities at the target points can then be obtained by summation over all the pixels as

$$A_m = \sum_{n=1}^{N_P} A_{Lmn} e^{i\Phi_n} \qquad \text{and} \qquad I_m = |A_m|^2 . \qquad (1)$$

A g error function is next defined as the metric for the closeness of the desired I_T distribution and the distribution I produced by the lens/filter combination:

$$g = \sum_{m=1}^{N_T} |I_{Tm} - I_m|^2 . \qquad (2)$$

The iterative design algorithm then comprises the following steps:

1) Calculate the A_{Lmn} pixel contributions.
2) Initialise the Φ_n pixel phase shifts to random or predefined values.
3) Calculate the initial error function g_0 using equations (1) and (2).
4) Select a random pixel ind x.

5) Modify the phase shift value of the selected pixel.
6) Re-calculate the error function.
7) If the new error function value is smaller than the previous one, keep new pixel phase shift value, otherwise reset pixel phase and error function to previous value.
8) Repeat 4) to 7) until changes in *g* become smaller than a predefined limit.

The critical elements of the algorithm are the initial filter phase values, the form of the error function and the way the 'random' pixel indices are generated. The error function can be much more complex than the one shown in (2). For example, it can be highly non-linear, or can even be changed automatically as the algorithm progresses.

In Figures 3, 4 and 5 examples of different filter designs for a 0.1 NA focussing lens and a λ=10.6 µm laser are provided with the black and white representing 0 and π phase shifts. The second column in the Figures is a diagram of the filter design with the third and fourth columns showing the light intensity distributions in the XZ and YZ planes respectively (the Z axis is parallel to the optical axis whereas the X and Y axes are perpendicular to the optical axis) and the fifth column shows on-axis intensity line scans. Figure 3a shows the single focused spot produced by the lens on its own. For the above parameters the single focused spot would be ~0.53 mm long (along the optical axis) and ~53 µm across. Figures 3b-3e show filters designed to produce two on-axis foci with a range of separations between them. Thus, Figure 3b shown two on-axis foci separated by 5 mm whereas the foci produced using the filter of Figure 3e are separated by 20 mm. The filters of Figures 3b to 3e are similar to a Fresnel zone plate, however, they have been optimised to produce only two foci (and not a whole series of diffraction orders) and so the efficiencies of the filters of the present invention are greater than the efficiencies achieved using conventional Fresnel zone plates.

Turning now to Figures 4a to 4d, the phase filters have been designed to produce more than two on-axis foci with Figures 4a, 4b and 4c having equal intensity foci. Figure 4d, on the other hand, shows a four level filter (the grey levels shown in this filter correspond to 0, $1/2\pi$ and $3/2\pi$ phase shifts) that produces three on-axis foci with intensity ratios of 2:3:4. Figures 5a to 5f show the designs of filters for generating more complex intensity distributions. Thus, Figure 5a shows a filter producing a 10 mm long axial line distribution with a 50% intensity spot at each end of the line i.e. ~15 mm apart; Figure 5b shows a filter that produces an intensity distribution similar to that of Figure 5a except that the intensity of the spots is equal to that of the line. In Figure 5c the intensity distribution is similar to that of Figures 5a and 5b except that the intensity of the line is 50% that of the spots. The filter of Figure 5d illustrates that the intensity distribution does not need to have cylindrical symmetry; this filter produces a 10 mm line that is tilted by 2° around the y axis. Figures 5e and 5f illustrate additional filter designs that produce a plurality of intensity peaks in the X-Z plane.

Thus, as has been shown, with the present invention there are few restrictions on the target intensity distributions that can be generated using the laser apparatus of the present invention. With the present invention the phase filter can be designed to meet the desired characteristics of the focal spot of the laser apparatus with respect to: the number of focal spots, spatial positions of the focal spots; the peak intensities; the axial resolution; the radial resolution; and the envelope function. Indeed, arbitrary intensity distributions in all three dimensions can be produced using the present invention. As the intensity distribution of the focal spot(s) can be designed in all three dimensions, high aspect ratio machining of the surface of a workpiece is possible. In particular, an extended on-axis line of equal intensity can be generated that is suitable to machine a channel without the need for the workpiece or the laser apparatus to be moved during the machining to re-focus the laser.

Although reference has been made to the filter being phase-only, it will be apparent that it is not essential for the filter to be phase-only.

Although the present invention has been described above with reference to conventional cutting, welding and machining processes, with the laser apparatus described above micromachining of structures with dimensions as small as 0.25 μm can be achieved. Such micromachining is normally performed using the LIGA process. Using the phase filter of the present invention in combination with conventional lens elements, micromachining with lasers can be achieved with aspect ratios comparable to those achieved with x-rays. Moreover, the laser apparatus is suitable for cutting or otherwise processing a wide range of materials including metals such as steel, wood, plastics including polymers such as PMMA, ceramics and silicon.

CLAIMS

1. Laser apparatus for use in material processing of a workpiece, the apparatus comprising a coherent or partially coherent light source, a housing containing one or more focusing elements and a phase filter, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on a desired intensity distribution of light incident on the workpiece which extends in at least one spatial dimension beyond the focused spot produced by the apparatus in the absence of the filter.

2. Laser apparatus as claimed in claim 1, wherein the phase filter is mounted in the pupil plane of the one or more focussing elements.

3. Laser apparatus as claimed in either of claim 1, wherein the phase filter is provided in a removable cartridge that is removably mounted within the housing.

4. Laser conditioning apparatus for use in material processing of a workpiece, the conditioning apparatus comprising an adapter housing containing a phase filter, the adapter housing having connection means for mounting the adapter housing between a coherent light source and one or more focusing elements, the phase filter having a plurality of regions with each region being assigned a predetermined phase shift from a plurality of possible phase shifts, the phase shifts of the plurality of regions being chosen in dependence on the desired intensity distribution of light incident on the workpiece which extends in at least one spatial dimension beyond the focused spot produced by laser apparatus in the absence of the filter.

5. Apparatus as claimed in any one of the preceding claims, wherein the phase filter is a programmable spatial light modulator.

6. Apparatus as claimed in any one of the preceding claims, wherein each region of the filter has a phase shift of either 0 or π radians.

7. Apparatus as claimed in any one of the preceding claims, wherein the phase filter produces a desired three dimensional geometry of the light incident on the workpiece.

8. Apparatus as claimed in any one of the preceding claims, wherein the phase filter produces a plurality of separate intensity peaks.

9. Apparatus as claimed in any one of the preceding claims, wherein the phase shifts of the plurality of regions of the filter are iteratively optimised with respect to the desired intensity distribution of the light incident on the workpiece.

10. Apparatus as claimed in claim 9, wherein the phase shifts of the plurality of regions of the filter are iteratively optimised using a direct binary search.

11. A method of manufacturing a phase filter for use in laser material processing apparatus, the method comprising the steps of: determining a desired intensity distribution of light incident on a workpiece which extends in at least one spatial dimension beyond the focused spot produced by the laser material processing apparatus in the absence of the filter; assigning initial respective phase shifts to a plurality of regions of the filter; determining an error factor with respect to the similarity of the intensity distribution generated using the assigned phas shifts to the desired intensity distribution; iteratively optimising the phase shifts

assigned to each region so as to determine final phase shifts for each region of the filter; and generating a phase filter with a plurality of regions, each region having the final phase shift determined by the iterative optimisation step.

12. A method as claimed in claim 11, wherein the assigned phase shifts are iteratively optimised using a direct binary search.

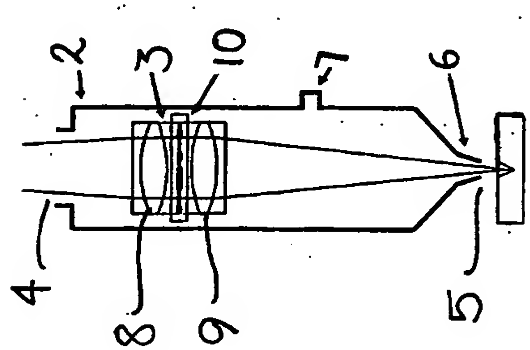


Figure 1a

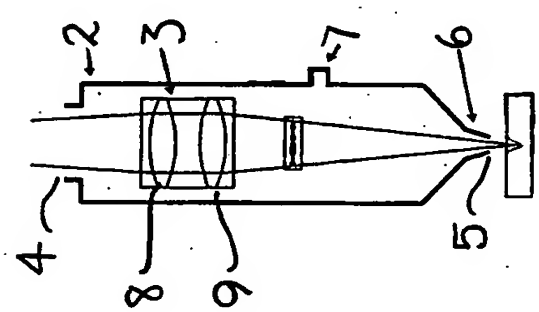


Figure 1b

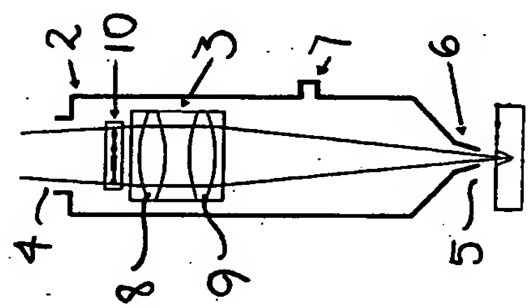


Figure 1c

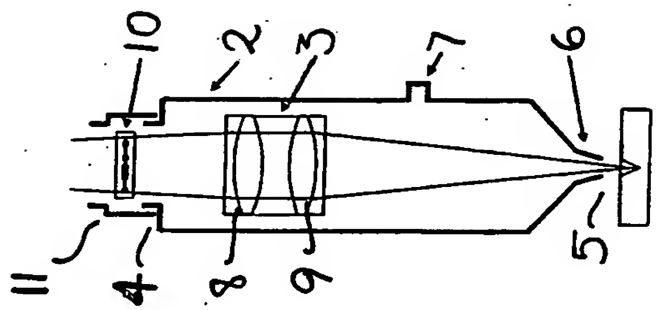


Figure 2

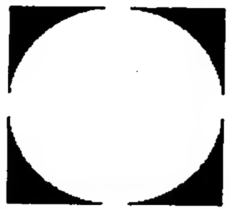
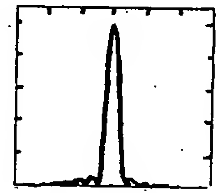
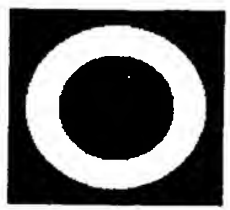
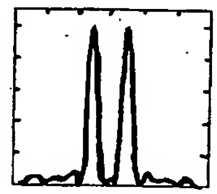
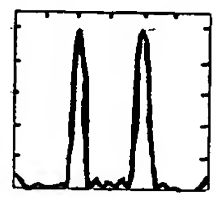
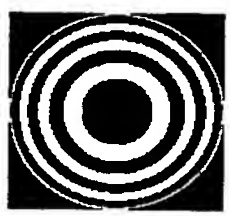
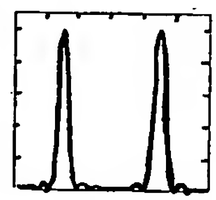
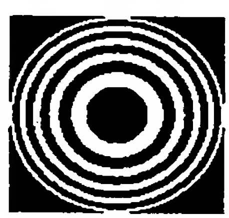
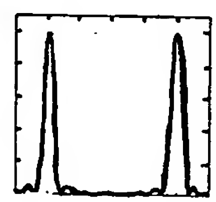
	filter	intensity in XZ plane	intensity in YZ plane	intensity on-axis
a 'lens-only' system single on-axis in-focus spot ~53μm across and 0.53mm long				
b 2 on-axis spots 5mm apart i.e. at x=0 z=±2.5 mm				
c 2 on-axis spots 10 mm apart i.e. at x=0 z=±5.0 mm				
d 2 on-axis spots 15 mm apart i.e. at x=0 z=±7.5 mm				
e 2 on-axis spots 20 mm apart i.e. at x=0 z=±10.0 mm				

Figure 3

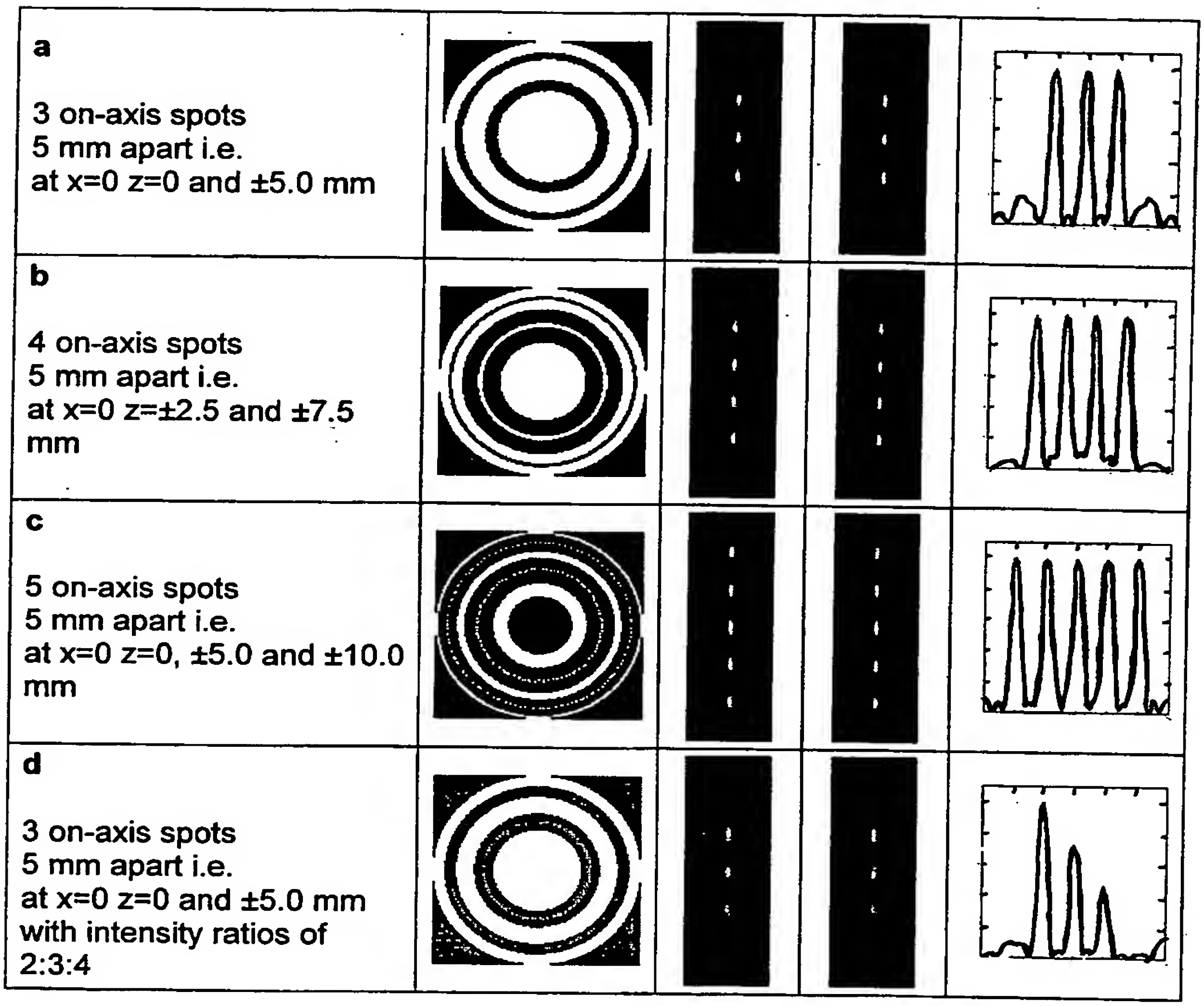

a
3 on-axis spots
5 mm apart i.e.
at x=0 z=0 and ±5.0 mm
b
4 on-axis spots
5 mm apart i.e.
at x=0 z=±2.5 and ±7.5 mm
c
5 on-axis spots
5 mm apart i.e.
at x=0 z=0, ±5.0 and ±10.0 mm
d
3 on-axis spots
5 mm apart i.e.
at x=0 z=0 and ±5.0 mm
with intensity ratios of 2:3:4

Figure 4

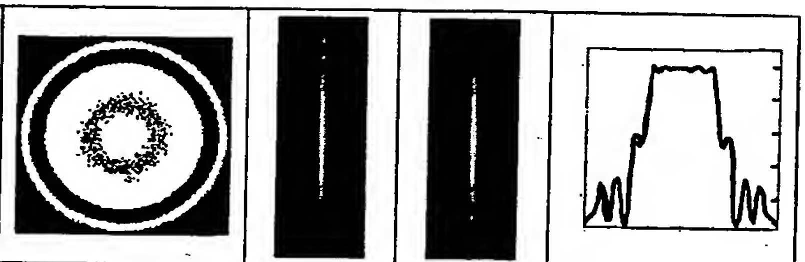
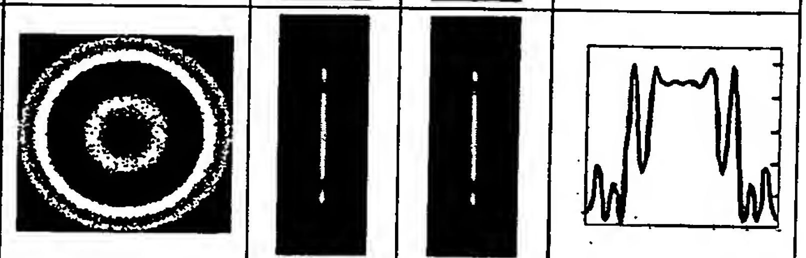
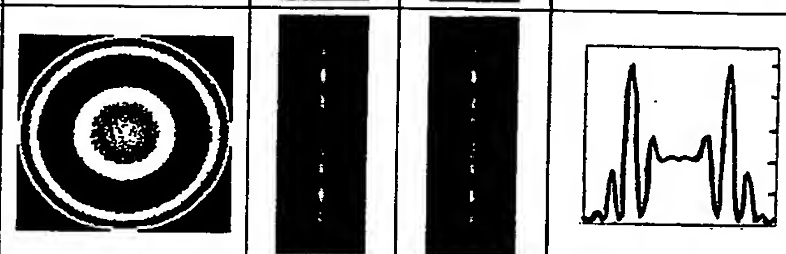
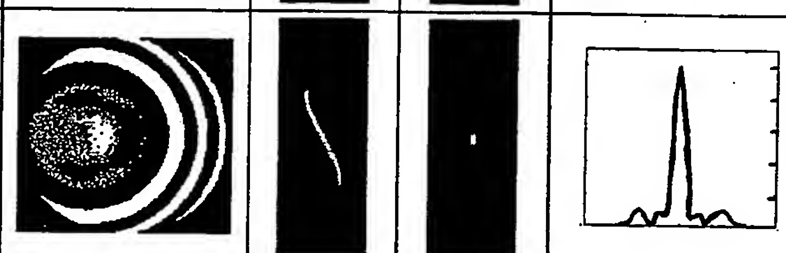
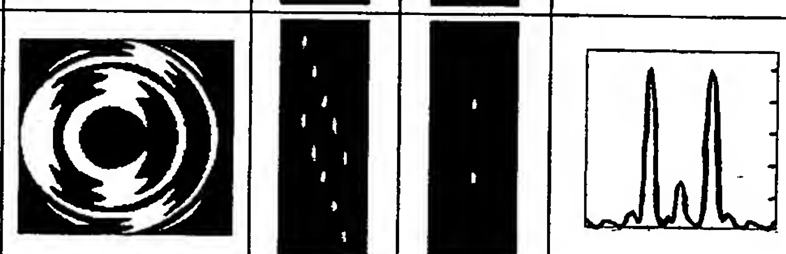
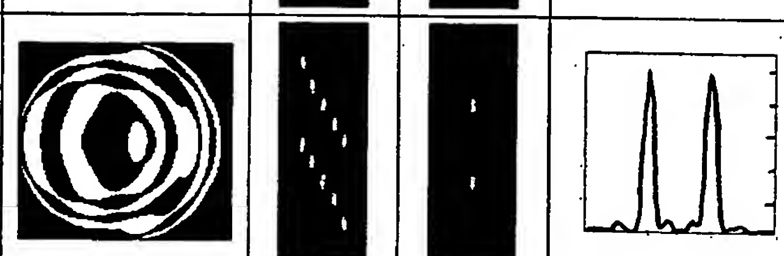
a 10 mm long axial line and two 50% intensity spots 15 mm apart i.e. at x=0 z=±7.5 mm	
b 10 mm long axial line and two spots 15 mm apart i.e. at x=0 z=±7.5 mm	
c two axial spots 15 mm apart i.e. at x=0 z=±7.5 mm and a 50% intensity 10 mm long line between them	
d 10 mm long line tilted by 2° around the Y axis i.e. with end points at x=-0.175 z=5 mm and x=0.175 z=-5 mm	
e 5 pairs of spots at x=-0.2, -0.1, 0, 0.1 and 0.2mm $z=z_0\pm5$mm with z_0=0, ±3.5 and ±7mm	
f 5 pairs of spots at x=-0.2, -0.1, 0, 0.1 and 0.2mm $z=z_0\pm5$mm with z_0=0, ±2.5 and ±5mm	

Figure 5

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 00/03496

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 B23K26/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 B23K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 679 469 A (MITSUBISHI ELECTRIC CORP) 2 November 1995 (1995-11-02) page 5 page 14, line 20; claim 26; figures 5,6 page 15, line 15 - line 57; figure 6	1-8
A	page 16, line 18 -page 17, line 4; figures 7,8 page 17, line 51 -page 18, line 2; figure 10 page 20, line 13 - line 16; figure 17 page 48, line 54 -page 49, line 20 page 47, line 37 - line 55; figure 103 page 45, line 15 -page 46, line 29; figures 96,97 page 37, line 42 -page 42, line 30; figures 82-91 page 35, line 17 - line 40; figures 73,74 page 31, line 44 -page 33, line 16; figures 63-68 -/--	9,11

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
11 December 2000	21/12/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Aran, D

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	column 2, line 47 -column 3, line 6 column 4, line 23 - line 39 column 8, line 58 -column 9, line 23; figures 2,3,5,10,12	11
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PCT/GB 00/03496

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